A visual understanding of optical rotation using corn syrup

M Nixon and I G Hughes
Department of Physics, Durham University, South Road, Durham DH1 3LE, UK

Email: i.g.hughes@durham.ac.uk

Abstract. In this paper a visual demonstration of optical rotation is presented, with content appropriate for use in a lecture demonstration as well as quantitative techniques suitable for an undergraduate-laboratory experiment. Linearly-polarized lasers of various wavelengths are propagated through a glass tube containing corn syrup. The rotation of the plane of polarization of the light is visible with the naked eye, making the experiment dramatic and engaging and aiding understanding of the phenomenon of optical rotation. In addition, we present a simple approach to quantitatively analyse data using only equipment commonly found in undergraduate teaching laboratories.

MSC: 78-01
Submitted to: European Journal of Physics

1. Introduction and Theory

In addition to providing a useful laboratory exercise and demonstrating further complex properties of light, optical rotation has various applications in research. By the mid twentieth century, the optical rotatory dispersions of different molecules were being used to give further insight into their structure. For example DNA and RNA were compared in a study which highlighted new differences between them [1]. Since then, the application of nonlinear magneto-optical rotation to extremely accurate measurements of magnetic fields has been explored [2]. Even more recently, optical rotation of the vacuum upon application of a magnetic field has been studied in detail as a way to further understand the complex properties of the vacuum [3].

The phenomenon that certain media can rotate the plane of polarization of incident linearly-polarized light is named optical activity. Optical rotation takes place when linearly-polarized light is passed through an optically active medium. An optically active medium is realised when a fluid contains molecules which are not their own mirror image, also known as chiral molecules. Due to this difference, right and left circularly polarized light move at different speeds through the medium, and hence get out of phase with one another. Since linearly-polarized light is a superposition of right and left circularly polarized light, this phase change changes the plane of polarization and optical rotation is observed.

Studying the specific optical rotation of a solution of chiral molecules is a fairly standard undergraduate laboratory exercise; see, for example [4] for an overview of the technique, and [5] and references therein for the specific case of sucrose. However, the actual effect of optical rotation is hard to visualise since the low concentration of sugar easily dissolvable in water limits the amount of rotation to much less than 360°. Therefore corn syrup has been used as the optically active medium due to its high concentration of chiral molecules [6-10]. Mahurin et al. [5] described a technique to visually demonstrate and quantify optical rotation which employed a photomultiplier tube. Here we present a simpler technique based on their setup which utilises the advances in technology that have been made since the paper was published. Now it is possible to record the rotation simply by taking a photo with a digital, or even mobile phone, camera. The images can then be analysed using simple computer code to quantify the effect.

The rotation angle depends on the wavelength of light used, the ambient temperature, the distance travelled through the medium and the concentration of chiral molecules, so a more standardised way to report these angles is required. The specific rotation is the most common of these, and is given by

$$[\alpha]_\lambda^T = \frac{\alpha}{l \cdot c} \tag{1}$$

where $[\alpha]$ is the specific rotation (deg dm^{-1} g^{-1} mL) with T and λ denoting its temperature and wavelength dependence, α is the observed rotation (deg), l is the pathlength (dm) and c is the concentration of solution used (g mL^{-1}) [11]. Around room temperature the dependence of the specific rotation on wavelength is much more dramatic than the temperature, hence the temperature dependence can be considered negligible.

When corn syrup is used it is possible to measure a value for the specific rotation at a given wavelength from a single image. Since polarized light is scattered preferentially perpendicular to the direction of propagation, with a maximum 90° from the plane of polarization, the light emitted from an optically active medium shows the evolution of the rotation [12]. Due to the high concentration of chiral molecules in corn syrup, the plane of polarization is fully rotated several times for visible light over a pathlength of around 0.5 m. Hence, minima and maxima of light are observed, with the separation between two successive minima/maxima corresponding to a 180° optical rotation. Measurement of this separation allows the calculation of a specific rotation, using (1), with either a rough reading for demonstration purposes or using the more precise technique described in the Method section.

In addition to finding the specific rotation, an easy extension is to construct the optical rotatory dispersion (ORD) [4], which is the specific rotation as a function of wavelength. The ORD can be used to give further insight into the structure of chiral molecules, as mentioned at the start of this section. For wavelengths far from an absorption resonance, the rotatory dispersion may be fitted using the Drude expression

$$[\alpha]_\lambda^T = \frac{A}{\lambda^2 - \lambda_0^2} \tag{2}$$

where $[\alpha]$ is the specific rotation as above, A is the rotation constant (deg nm^2 dm^{-1} g^{-1} mL), λ_0 is the dispersion constant (nm) and λ is the wavelength of light used (nm) [11].

2. Method

The experimental setup is shown in figure 1, where light from a laser is enlarged using a beam expander before passing through a linear polarizer and glass tube containing corn syrup. A camera located parallel to the length of the tube is used to record images of light scattered from the corn syrup. The tube used for the data presented here was of 65 cm in length and 5 cm in diameter. The exact dimensions are not important, however they should be of the same order of magnitude to ensure the beam can be expanded and that enough cycles of rotation are included. Expanding the laser beam increases the visual impact of the experiment by heightening the contrast between bright and dark patches. Where a beam expander is not available, the enlargement may be carried out using a microscope objective and collimating lens. For a simple demonstration, for example in an undergraduate lecture, this is the only apparatus required and the rotation may be easily observed with the naked eye. To increase the impact of the demonstration, a rotatable linear polarizer should be used and rotated to show how the bright and dark fringes move. Different colour lasers may also be used to show directly the impact of wavelength on rotation.

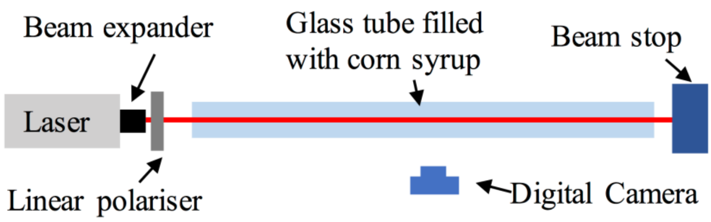

Figure 1: The setup used for the experiments as viewed from above. A laser is expanded and made linearly polarized before being directed down a glass tube containing corn syrup. The optical rotation is imaged using a digital camera.

Each rotation image should then be transferred to a computer and cropped so that only the bright and dark fringes are included. A simple program may be written to find an average distance between minima or maxima for a particular wavelength in pixels. Depending on the time frame of the experiment and the experience level of the students, writing the program could be used as an exercise linking practical work and programming or the program could be simply supplied to the students. The separation value in pixels can be simply converted to a distance by taking and using an image of the setup with a metre rule placed along the tube, making sure that no change to the camera position occurs. Finally, the specific rotation may be found using (1).

For an ORD measurement, specific rotations should be determined over a wide range of laser wavelengths, for example here lasers of wavelength 408 nm, 543 nm, 594 nm, 632.5 nm and 674 nm were used. These were chosen for their range of colours and ease of acquisition, however any available visible wavelengths could be used. The ORD should then be determined, by plotting the specific rotations as a function of the laser wavelengths, with the values verified using a spectrometer where available. The dispersion should then be compared to the Drude expression, (2), and by performing a least-squares fit (see, for example, Chapter 6 of Hughes and Hase [13]), the constants and line of best fit determined.

3. Results and Discussion

Figure 2 shows two images taken at λ = 632.5 nm as the laser propagates through corn syrup. Between the two images the linear polarizer was rotated by 90°, which is equivalent to viewing the tube from the side and then from above. These observations help to clearly explain the basic principles of optical rotation. Visible in both images are the characteristic bright and dark bands expected when optical rotation is occurring. The key difference between the two images is that where one is bright the other is dark, and vice versa.

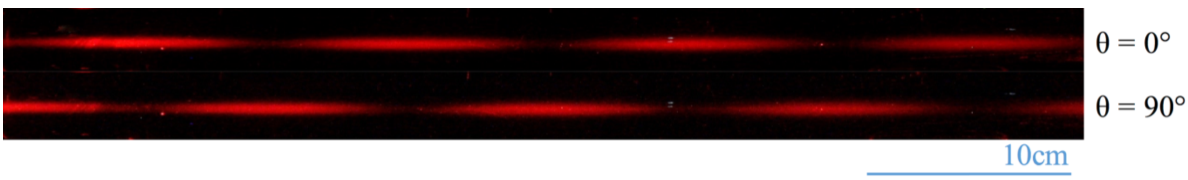

Figure 2: Images of the rotation of the 632.5 nm laser through corn syrup with the linear polarizer at θ = 0° and 90°, as labelled in the figure, analogous to viewing the tube from the side and from above. The difference between the images shows that the light is indeed rotating not simply varying in intensity.

Recalling that the scattered intensity has a maximum 90° from the plane of polarization [5], the combination of these two images confirms that the polarization of the light really is rotating, since the intensity of the scattered light is not uniform about the tube. As an additional exercise, it is possible to create a 'movie' by recording images of the tube as the polarizer is rotated in 5° increments and concatenating them. This too provides a vivid demonstration of the rotation in action – in the case of a demonstration, showing such a movie or rotating a polarizer by hand would be very effective.

Further images showing the rotation of light through corn syrup at four example wavelengths are given in figure 3. More of the black background is included for these images for visual clarity than should be left in for any computational analysis. The first key difference between the images is the dramatic reduction in intensity observed with the blue laser. When far from a resonance of corn syrup, it's possible to neglect the effects of absorption. However when near to a resonance, as in the case of the blue laser, the refractive index is increased. Due to the Kramers-Kronig relations [14], which link refractive index and absorption, a dramatic increase in the absorption is observed hence the intensity of the laser drops significantly towards the far side of the medium. Since the laser was able to propagate part way down the tube, it was still possible to analyse the left hand side of the image. Figure 3 can also be viewed as a visualisation of the physics encapsulated in the Kramers-Kronig relation: stronger matter-light interaction is needed to observe more optical rotation, which is achieved by reducing the wavelength, but the concomitant increase in the absorption coefficient limits how close to resonance one can operate.

The second point of interest in these images is the clear wavelength dependence of the rotation, with a visible increase in the rotation rate at shorter wavelengths. This general trend in the specific rotation is consistent with the Drude expression, however to verify the match the ORD has been constructed. To determine a specific rotation, as given by (1) and discussed in the Method section, both the pathlength and concentration of solution must be known. Corn syrup is a complex mixture of different kinds of sugars and so determining a precise concentration is not possible. To enable the ORD to be included in such an investigation the concentration was given the value of 1 g mL^{-1}. A pure sucrose solution would give a known concentration, however, as previously discussed, it was found to be unfeasible to prepare high enough concentrations in an undergraduate lab to give the visible rotation necessary for this technique to work.

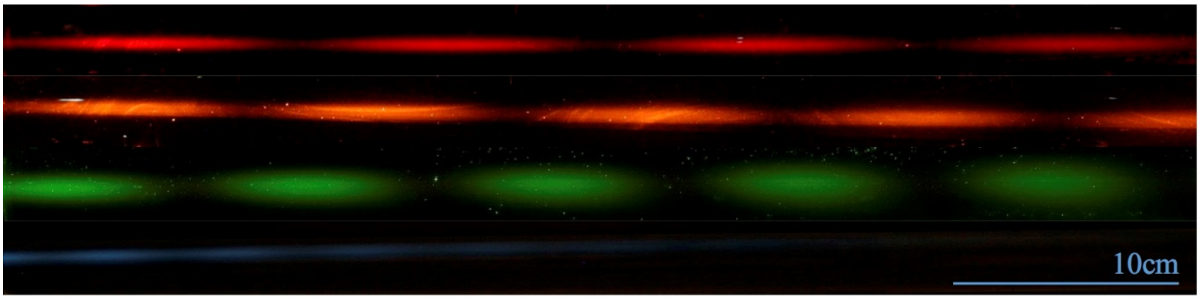

Figure 3: Images of the rotation of laser light through corn syrup. Four example wavelengths are shown here, from top to bottom 632.5 nm, 593.8 nm, 543.3 nm, and 407.6 nm. Note the increased rate of rotation for shorter wavelengths in accordance with the Drude expression, and the significantly increased extinction of the light for short wavelengths, as predicted by the Kramers-Kronig relation.

The ORD is shown in figure 4, with specific rotations calculated from the five measured wavelengths. A powerful technique to compare experimental data with theory uses the χ^2 statistic [13]. For each experimental point the normalized residual – the deviation between the experimental measurement and the expected theoretical value, divided by the experimental uncertainty – is calculated. The sum of the squares of the normalized residuals is the χ^2 statistic. The reduced χ^2 value is obtained by dividing by the number of degrees of freedom – the number of experimental data points less the number of parameters in the theoretical model. Optimal values of the parameters in the theoretical model are obtained by minimising the value of χ^2. For a good fit between theory and experiment it is expected that the minimum value of χ^2 should be approximately equal to the number of degrees of freedom, such that the reduced χ^2 value is 1 [13]. For the Drude expression of equation (2) the best-fit model is included in figure 4 as the smooth line. With data taken from the images above, Drude constants of $A = (4.89 \pm 0.02)\times10^7$ deg nm^2 dm^{-1} g^{-1} mL and $\lambda_0 = (166 \pm 6)$ nm were obtained. The fit to the data in figure 4 yields a reduced χ^2 value of 1.25; this confirms the applicability of the Drude model. The fitting of such a theoretical curve provides another useful exercise for students due to its non-linear nature.

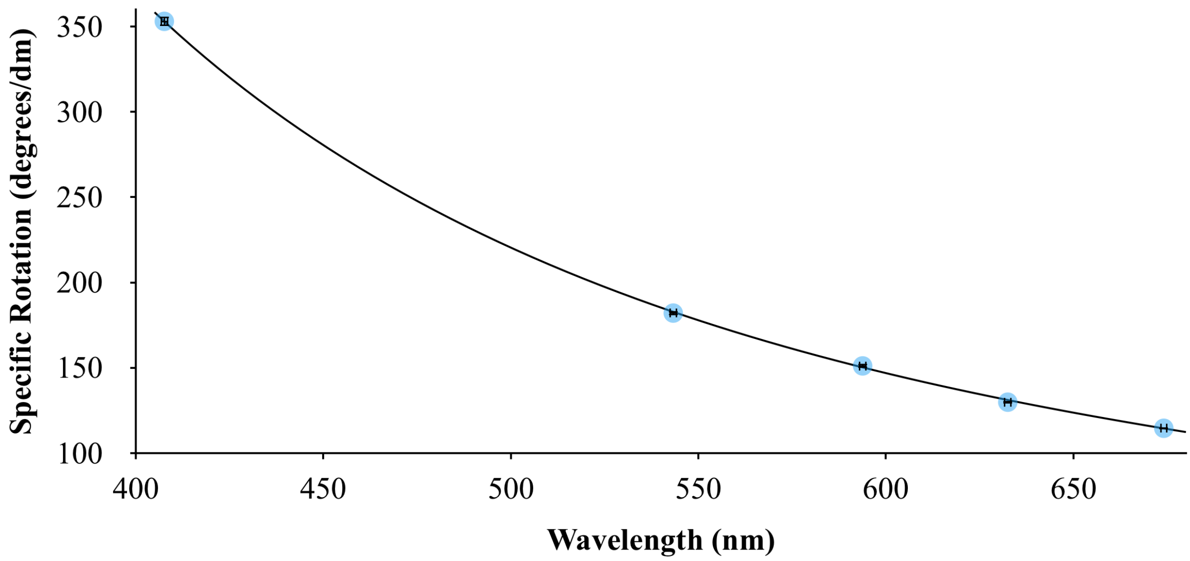

Figure 4: The optical rotatory dispersion showing specific rotation as a function of wavelength. A theoretical curve based on the Drude expression of (2) and error bars have been added where y error bars are too small to be seen. Standard least-squared χ^2 minimisation techniques [13] were used to obtain the best-fit parameters $A = (4.89 \pm 0.02)\times10^7$ deg nm^2 dm^{-1} g^{-1} mL and $\lambda_0 = (166 \pm 6)$ nm. A reduced χ^2 value of 1.25 for the optimised parameters illustrates the validity of the Drude model for these data.

Schneider [15] showed that a visualisation of the evolution of the polarisation of light within a birefringent solid, such as a Plexiglas rod, is possible; and that quarter and half-wave plates could be constructed by cutting off pieces with the desired retardation length. In theory, one could do the same with the medium studied in this work – by either controlling the length of the tube containing the corn syrup, or by appropriate dilution of the concentration.

4. Conclusions

In this paper, a simple experiment demonstrating the concept of optical rotation has been described. The setup is uncomplicated enough for use in a lecture demonstration, however the depth of detail possible also lends itself to an undergraduate laboratory experiment, whilst still involving only inexpensive equipment likely owned already. The method of recording data is simplified compared to previous work; it is now possible just to take a photograph. This provides an engaging way to carry out quantitative measurements, with the use of basic programming enabling the images to be analysed whilst linking coding and laboratory based physics. The calculations of specific rotations and optical rotatory dispersions make this experiment both visually vivid and scientifically rigorous.

Acknowledgements
The authors would like to thank the laboratory technicians at the Physics Department, Durham University for their expert assistance; J Keaveney and R Mathew for reading the manuscript and suggesting improvements; and M Szablewski and A Hindmarch for their encouragement.

References
[1] Samejima T and Yang J T 1964 *Biochemistry* **3** 613
[2] Budker D, Kimball D F, Rochester S M, Yashchuk V V and Zolotorev M 2000 *Phys. Rev.* A **62** 043403
[3] Zavattini E et al (for the PVLAS collaboration) 2006 *Phys. Rev. Lett.* **96** 110406
[4] Compton R N and Duncan M A 2016 *Laser Experiments for Chemistry and Physics* (Oxford: Oxford University Press) Chapter 20
[5] Mahurin S M, Compton R N and Zare R N 1999 *Journal of Chemical Education* **76** 1234
[6] Freier G and Eaton B G 1975 *American Journal of Physics* **43** 939
[7] Koubek E and Quinn H 1989 *Journal of Chemical Education* **66** 853
[8] Becker R 1993 *Journal of Chemical Education* **70** 74
[9] Pecina M A and Smith C A 1999 *Journal of Chemical Education* **76** 1230
[10] Knotts M E and Rice J M 1999 *Optics and Photonics News* **10** 64
[11] Mason S F 1982 *Molecular Optical Activity and the Chiral Discriminations* (Cambridge: Cambridge University Press)
[12] Barron L D 1982 *Molecular Light Scattering and Optical Activity* (Cambridge: Cambridge University Press)
[13] Hughes I G and Hase T P A 2012 *Measurements and Their Uncertainties* (Oxford: Oxford University Press)
[14] de L. Kronig R 1926 *J. Opt. Soc. Am.* **12** 547
[15] Schneider W B 1991 *American Journal of Physics* **59** 1086